Drilling Optimization in Deep Horizontal Wells
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Abstract

In northern Oman, a project for twelve horizontal wells required drilling optimization in a field that presented various geological, drilling, and well construction challenges, including inter-bedded shales, abrasive reservoir, severe stick/slip, sidetracking issues, and low rates of penetration (ROP).

The well design planned for the 12 1/4-in. and 8 3/8-in. vertical sections, building from vertical to a 15° inclination to sidetrack at 8 3/8-in. and landing followed by a 6 1/4-in. lateral.

Several collaborative drilling practices and technologies were implemented in the 12 1/4- and 8 3/8-in. vertical sections and the 8 3/8-in. curve section. In the vertical sections, ROP was increased by introducing a closed-loop vertical drilling system with motors and by optimization of bit and BHA design, which also improved run length. The pilot hole was deviated from vertical to facilitate sidetracking. The 8 3/8-in. curve was drilled using a point-the-bit rotary steerable system (RSS), and drilling performance was enhanced with a power section to drill in a single run. Deviating to 15° inclination resulted in a 100% success rate in sidetracking. Many options were tried to optimize BHA design, including continuous bit optimization to find the best PDC bit for steer-ability, durability, ROP, and stick/slip reduction.

This optimization approach lead to a total of 7.5 drilling days saved in the AFE. The use of motors and the vertical drilling system saved 1 day of AFE. Using a point-the-bit RSS to sidetrack from a deviated pilot hole and adding a PDC bit for the curve saved an additional 6 days. High quality of the wellbore saved 0.5 days in avoiding a wiper trip and stuck incidents.

The optimization techniques improve the performance of drilling horizontal wells to consistently attain 100% well delivery with a smooth borehole. The method represents a step change in drilling horizontal wells using the fit-for-purpose approach (i.e., optimized trajectory, proven bit, recommended drilling parameters derived from simulations compared to actual) to deliver wells in a cost-effective manner.

Introduction

In northern Oman, drilling horizontal wells is a challenge and requires an optimization approach to address the problems so that excessive drilling and completion costs can be minimized. This optimization approach involved revisit to the field offset wells data, revision to trajectory design and bit selection, drilling fluid and drilling practices in the 12 1/4in and 8 3/8in sections.

This field is in North of Oman and was discovered in 1979, first brought to production in 1981. Most of the reserves present in the field are light oil. They are contained in a 22m oil layer at a depth of 3175m subsea. This specific hydraulic unit also showed low permeability at the sheet sands of the lower Gharif and Al Khlata (LG/AK) reservoirs (sandstone). A significant volume of oil reserves are, in principle, held at shallower horizons in middle and upper Gharif. The target reservoir is primarily the Al Khlata (AK). Fig. 1 outlines the different reservoirs that are targeted in this field.
Drilling horizontal wells in this field to reach the target reservoir presents many geological and drilling challenges. In this paper, we discuss the means to reach the target in an optimized way using the continuous improvement technique from well to well in the twelve horizontal wells drilled with the directional drilling contractor. We also consider the drilling days saved using the optimization methods.

To date, 23 wells have been drilled and completed in the lower sandstone reservoir, which belongs to Al Khlata formation. These penetrated the entire geological column in multiple horizons. The first eleven wells were drilled prior to the drilling optimization approach; these wells incurred high well costs and delays in productions. The drilling optimization approach started with drilling the twelfth well, and various approaches were tried and continued until the last, the twenty-third, well was drilled. The initial eleven drilled wells in the field established important rock qualities and hydrocarbon saturations, which became the key factors for future reservoir management and field development in subsequent wells.

Over the last 3 years of field operations, some concerns have been raised as to whether the well-cost scenario for this well design would allow future field development in lower productivity reservoirs such as Al Khlata and lower Gharif. The cost of the earlier wells was the baseline for the drilling optimization project, and there was to be successive cost improvement in each well drilled after the start of the optimization program. This paper focuses on drilling optimization in the 12 1/4-in. vertical and 8 3/8-in. buildup section because these sections required significant performance uplift.

A typical well design is shown in Fig. 2.

In a typical well, the 17.5-in section is followed by a 12 1/4-in. vertical section. In the 12 1/4-in section, performance improvement was a challenge because of an increase in penetration rates in the loss zones. The goal was to drill through these zones in shortest period of time, at the same time ensuring the verticality; in the past, correction runs were required to bring the well back to vertical. Losses in the 12 1/4-in. section are very dominant in this field because of the unconsolidated nature.
of the shale formations (Natih and Mafraq). Often, drilling with a conventional rotary bottomhole assembly (BHA) requires extra time for drilling the section because of multiple correction runs. In the past, losses in the section have exposed the BHA to a higher possibility of sticking. As the formations are reactive, greater exposure due to slow drilling requires more conditioning trips to prevent difficulty in running the 9 5/8-in. casing. A closed loop rotary steerable (push-the-bit) system with a performance mud motor above it was used to set the benchmark performance for the field. This introduction of this technology saved the operator 1 day in the AFE by drilling faster and having a smooth 9 5/8-in. casing run since formations were exposed over a shorter period of time. In the past, packed vertical BHA were used with string stabilizers; this presented a challenge in terms of stick/slip since multiple stabilizers were exposed to different formation types at the same time. The 12 1/4-in. vertical section in this field consists of various inter-bedded formations. The introduction of a closed-loop rotary steerable system (RSS) not only improved the on-bottom penetration rates but also optimized the drilling performance by eradicating excessive stiff stabilized assemblies causing stick/slip. At the same time, the extended power motor above the RSS helped decouple the bit-related stick/slip from the BHA, resulting in better on-bottom penetration rates.

Bit selection in this section is pivotal because of the nature of the formations (i.e., shales with inter-bedded abrasive layers often leading to bit balling and hard banding during back reaming). A customized PDC bit design with a 5-blade, 19-mm cutter design (efficient light-set cutting structure bit, with durable cutter technology), with a steerable-friendly design along with the closed-loop rotary drilling system ensured very good borehole quality with minimal stick/slip and lateral vibrations.

The 12 1/4-in. section performance was deeply affected by the bit selection; this section consists of unstable shales with inter-bedded abrasive formations (i.e., the Natih and Mafraq) which create issues of poor hole cleaning, the potential for bit balling, tight intervals, hard back reaming, and problems while tripping. This fit-for-purpose technology and customized bit design resulted in a record of 19.2 m/hr drilling rate and a total drilled interval of 1849 m. It is worth to mention that in the past, up to two or three runs were needed to reach section TD.

The 8 3/8-in. Pilot Hole
Drilling optimization started from well twelve. Of the total twenty three wells in this field, most of the wells were drilled with the pilot holes. Two of the wells were drilled without a pilot hole; in these, the 8 3/8-in. buildup section was drilled only where the geologists and geophysicists were very certain about the buildup section direction. Drilling the pilot hole was a challenge because of difficulties drilling through the Gharif sand, and Al Khallata formations which are abrasive sandstones with medium hardness, and drilling the formation often calls for more than one BHA run. Initially, pilot holes were vertically drilled using either packed assemblies or mud motors to enhance the performance. When this drilling optimization initiative started, one of the objectives was to drill the pilot hole more efficiently and performing cost-effective sidetracking over a cement plug after the wireline logging operation. The optimum approach which was tried was drilling the pilot hole as an S-shape (i.e., build to 15° inclination and then drop to vertical instead of drilling a purely vertical pilot hole). This was done using a point-the-bit RSS to deliver better penetration rates with good borehole quality. Sidetracking was facilitated by the inclination in the hole; this inclination enabled us to sidetrack successfully over the cement plug using the BHA gravity effect to sidetrack. Using this technique eliminated the need for a dedicated BHA run. It is worth mentioning the cost savings from the avoidance of whipstock, since in the past, prior to the optimization study, many times whip-stocks were used to sidetrack when the sidetrack over cement plugs failed.

The 8 3/8-in Sidetrack Section/Buildup Section
The 8 3/8-in. sidetrack section/buildup section is pivotal with respect to the drilling optimization since various approaches were applied to optimize the drilling in this section. Various aspects were changed to improve the performance. These changes included

- Revision to trajectory design
- Revision to cement plug recipe
- Sidetracking technique
- BHA design
- Drilling parameters monitoring and mitigations
- Mean specific energy management

The objective of this section is to drill 900 m across the ultra-hard upper, middle, and lower Khuff, upper Gharif, middle Gharif, lower Gharif, and Al Khallata formations. The confined compressive strength (CCS) of these layers varies between 45 and 60 x 10^3 psi, and in previous drilling they have demonstrated extremely abrasive features.

Trajectory design was reviewed by nudging the pilot hole section instead of drilling vertical (Fig. 3) and by splitting the build rates in the buildup section, with 6° to 7°/30 m buildup rates in the beginning of the section dropping to 3°/30m when the Haushi limestone is reached because by then significant wear is expected on the motor/rotary steerable sleeves and directional response is reduced. This trajectory design revision not only facilitated the sidetracking over a cement plug avoiding excessive cost of whip-stocks, but also saved cost in eliminating the excessive BHA trip for the bit and the need for replacement sleeves for the tools.
The pilot hole cement plug was revisited to facilitate sidetracking using the point-the-bit RSS. Kicking off in this field in the upper Khuff with CCS on the order of 30 to 40 x 10^3 psi has proven to be a very challenging operation. The traditional approach calls for three cement plugs for abandonment and sidetracking purposes; the first and second plugs are for plugging and abandoning purposes, and the third (topmost) plug is set as a base for the openhole whipstock for sidetracking purposes. Some design modifications have been done, such as modifications to the cement slurry. An 18.6 kPa/m, cement slurry was designed for the kick-off. The slurry has the following properties:

- Controlled fluid loss below 100 cc to prevent dehydration of the slurry across and permeable formation and control the free water to 0%
- High compressive strength, which has an initial set of 8 hours

The goal was to achieve 1200 psi after 12 hours and 3000 psi after 18 to 24 hours. The rheology has been enhanced to be properly mixed and to achieve a degree of turbulence while displacing it in the annulus to enhance the displacement efficiency.

The above recipe helped in the deviated pilot hole to sidetrack successfully using the point-the-bit RSS and then later drill the 8 3/8-in. buildup section in a single run.

Sidetracking over a cement plug from vertical has been the initial procedure in the twelve horizontal wells drilled. However, the method often faced difficulty sidetracking using the steerable motor assembly when the pilot hole was vertical; these cases often required multiple runs to sidetrack from the pilot hole, raising the well AFE. Openhole whip-stocks have been used in a few wells in which sidetracking over a cement plug was not achieved, which was another added cost. This was resolved by introducing the deviated pilot hole trajectory design, along with the fit-for-purpose technology (i.e., point-the-bit
RSS to sidetrack and then drilling the buildup section in one run). This also eradicated the need for a whipstock, and drilling could proceed from the beginning until the end of the section in one run, overcoming all drilling challenges with benchmark penetration rates. Performance was further enhanced, leading to a saving of 6 days altogether when a high-power mud motor was used above the point-the-bit RSS. This not only improved the penetration rates, but also minimized the stick/slip by the extra RPM delivered by the mud motor.

**Fig. 4** shows the benefits of drilling a deviated pilot hole. In the following figure, sidetracking in the deviated pilot hole is compared to sidetracking using a vertical pilot hole. It is evident that sidetracking from a deviated pilot hole is much quicker in terms of operation hours compared to a sidetracking from a vertical pilot hole. A vertical pilot hole requires a dedicated BHA to sidetrack and then trip to pick up the directional BHA for the buildup section. In addition, with a vertical pilot hole, sidetracking over a cement plug is not always possible, thereby triggering the need for a whipstock.

![Sidetrack Process (Hrs)/well](image)

**Fig. 4 Rig-time savings using the new innovative trajectory design.**

The point-the-bit RSS not only helped to sidetrack from the pilot hole, but also helped to pump up to 0.037 m³/s in the 8 3/8-in. section. The better hole cleaning leads to a clean borehole, and since the entire string rotates with the string RPM, there is better cuttings transfer and higher penetration rates since no sliding is required. Oil-based mud was employed in drilling the 8 3/8-in. section, which helped reduce the fluid loss, thus improving hole integrity. Performance was further enhanced when a power section was used above the point-the-bit RSS, with the proven 16 mm, 6-bladed PDC bit solving the concerns of hole cleaning and on-bottom ROP.

BHA design has been pivotal in the drilling optimization of this project, with a particular focus on sidetracking and drilling the buildup (8 3/8-in. section). In the earlier eleven wells, multiple BHA runs were conducted to sidetrack, and many BHA runs were used to drill the buildup section because of various factors. One of the major factors was excessive equipment wear (i.e., sleeve, bit, and stabilizers wear) with stick/slip, which often triggered the need for a turbine BHA with impreg bit once the reservoir was approached. This system was replaced by the revised trajectory design and fit-for-purpose point-the-bit RSS with customized bit design which facilitated sidetracking and building up the section in a single run, with highest on-bottom penetration rates. Another added advantage of the RSS is the smooth borehole quality, which reduces the chances of sticking while drilling, minimizes back-reaming requirements, and ensures smooth and fast 7-in. liner runs, along with eradication of turbine and impreg run costs. To combat the wear in the laminated formations while drilling, tungsten carbide sleeves for the RSS were used with an optimized bit design.

Near-bit inclination from the RSS helped us to make proactive decisions with respect to trajectory design in contrast to the situation with conventional drilling assemblies.

A16-mm cutting structure bit, with full steer-ability features, leveraged by torque reduction elements and enhanced cutter performance against severe impacts, proved to be a fit-for-purpose bit for the application.

The proposed bit is a matrix body bit, designed specifically for directional applications where superior torque control is required. It has been engineered specifically in terms of profile, cutting structure, and gauge geometry to enhance drilling performance when used in combination with rotary steerable tools or performance drilling when mud motors and RSS are combined.

The implementation of the above bit in the buildup section of the last well drilled in this field doubled the traditional ROP, delivering 1000 m through the hard Khuff, Gharif, and Al Khlata formations, with an ROP of 15 m/h compared to the previously achieved penetration rate in this field. Furthermore, the bit dull grading was 2-3-WT-A-X-I-NO-DTF.
The bit driven by the point-the-bit RSS featured a 6-bladed, 16-mm cutter design (short bit length and steerable profile), engineered cutter back racks for optimal ROP, a stable technology cutting structure, optimized gauge design to boost the dogleg requirement and reduce the lateral shocks and stick/slip behavior.

Shocks and vibrations have been important issues in the earlier wells drilled in this area; after the optimization campaign started, a proactive approach on waste energy management and equipment damage was applied.

In addition to the RSS, oil-base mud, and optimum bit design, another important area to explore was the effective use of available energy in terms of RPM and weight on bit (WOB).

In this project, an attempt was made to acquire data concerning rock strength as well as actual meter-to-meter drilling parameters. This was to ensure that adequate magnitudes for RPM and WOB were used, whilst avoiding stick/slip and whirl tendencies.

In this context, the concept of mechanical specific energy (MSE) was introduced. This involves a comparison between the magnitudes of the rock strength per drilled layers versus the amount of energy required to drill that specific volume of rock in one of the offset wells.

The MSE calculation was done with the data that came from the drilling recording system of one of the wells. Fig. 5 shows the WOB, RPM, torque, and MSE plotted against depth. It should be noted that erratic outcomes were observed beyond 2000 m and continued to the total depth of the well.

The MSE equation below was used to estimate mechanical specific energy.

$$MSE = \left( \frac{WOB}{Ab} \right) + \left( \frac{120 \times \prod \times N \times T}{Ab \times ROP} \right),$$

Eq. 1

where:
MSE: mechanical specific energy (psi)
WOB: weight on bit (pounds)
Ab: Borehole area (in.$^2$)
N: RPM
T: Torque (ft-lb)
ROP: Rate of penetration (ft/hr)
From Fig. 5, we can determine that the average MSE in the interval 2100 m to 2500 m is 62,890 psi, whereas the rock strength showed 52,000 psi on average for the hardest layers (upper, middle, and lower Khuff). This additional energy is interpreted as “wasted energy” in the form of erratic torque which is caused by stick/slip and lateral vibration.

Field operations have shown several times the tendency of the BHA to stall. This has traditionally required various drill-off tests, which are carried out to reduce the erratic torque trend seen in the shown torque chart.

**Conclusion**

In conclusion, the main challenge in the northern Oman wells is in the 12 1/4-in. section; this challenge was addressed using the closed-loop vertical rotary RSS with the recommended bit to deliver the optimum performance with true verticality, eliminating any correction runs and excessive wiper trips and improving penetration rates.

In the 8 3/8-in. section, drilling optimization proved to be a step change in the drilling of formations with UCS ranging from 5 to $5 \times 10^3$ psi. Using the point-the-bit RSS along with a power section above delivers the best penetration rates with optimum trajectory control and avoids any extra BHA trips and well construction problems. The introduction of oil-base mud facilitated drilling through reactive shales that would otherwise cause borehole instability. Optimization in the bit design helped to achieve the remarkable performance with the point-the-bit RSS with steer-ability and durability.

The technology and engineering approach helped save costs in 12 1/4-in. and 8 3/8-in. sections by avoiding corrections runs, multiple BHA trips (turbine and impreg), undesired deviation, poor borehole quality, repeated kickoff plugs, use of a whipstock, and casing run problems. This paper will serve as a reference for similar horizontal drilling operations locally and worldwide.

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